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MECHANICAL PROPERTIES OF ELEMENTALLY BLENDED Ti-6Al-4V

NEAL R. ONTKO

Materials Engineering Branch
Systems Support Division

November 1986

Final Report for Period June 1983 - September 1985

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533

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This technical report has been reviewed and is approved for publication.

Neal R. Ontko

NEAL R. ONTKO
Project Engineer
Materials Engineering Branch

Clayton L. Harmsworth

CLAYTON L. HARMSWORTH
Technical Manager
Engineering & Design Data
Materials Engineering Branch

FOR THE COMMANDER

Theodore J. Reinhart

THEODORE J. REINHART, Chief
Materials Engineering Branch
Systems Support Division
Materials Laboratory

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This effort evaluated Ti-6Al-4V material manufactured from an elementally blended powder. Powders from a master alloy of Al/V and Ti sponge fines were processed into specimen blanks by state-of-the-art PM technology.

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AF Wright Aeronautical Laboratories
Wright-Patterson AFB, OH 45433-6533

PREFACE

This report was prepared by the Materials Engineering Branch (AFWAL/MLSE), Systems Support Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Program Element 62102F, Project 2418, "Metallic Structural Materials," Task 241807, "Systems Support," Work Unit 24180703, "Engineering & Design Data."

The work reported herein was performed during the period June 1983 to September 1985, under the direction of the author, Neal R. Ontko (AFWAL/MLSE). This report contains data and a description of the test effort by Southern Research Institute and AFWAL/MLSE. Report No. SoRI-EAS-84-1111, "Mechanical Properties of Ti-6Al-4V PM Alloy," was received in November 1984 documenting portions of this effort.

The author wishes to thank Mr. Stuart Starrett and the Southern Research Institute (SoRI) for their efforts in testing the material and assembling this report, Dr. F.H. Froes (AFWAL/MLLS) and Mr. Gerald Petrak (AFWAL/MLSE) for their guidance, and messers Russell Cervay, Donald Woleslagel, and John Eblin (University of Dayton Research Institute) for their assistance and efforts.

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SECTION I

INTRODUCTION

This work was undertaken for the purpose of establishing mechanical properties data on "Elementally Blended" Titanium-6Al-4V manufactured by an innovative powder metallurgy process. A total of 100 test specimen blanks were purchased by the Air Force Materials Laboratory from Imperial Clevite (Gould, Inc.) Cleveland, Ohio. Powders from a master alloy of Aluminum and Vanadium comprising 10 percent of the total weight was blended with commercially available powder from Titanium sponge fines. This blend of powders was then cold pressed, sintered and hot isostatically pressed. Details of the processing are considered proprietary. Comparative costs for this material are substantially less than powders made from pre-alloyed billets such as Rotating Electrode Process (REP) titanium.

Four different types of evaluations were performed on the material; tension, fatigue (smooth and notched), crack growth rate, and fracture toughness. The tensile evaluations were performed at room temperature (RT), 400°F and 800°F by Southern Research Institute (SoRI), Birmingham, Alabama. Smooth and notched fatigue tests at RT and 800°F, crack growth rates at RT, and fracture toughness testing at RT were also completed at SoRI. Fatigue testing at 400°, crack growth rates at 400°F and 800°F, and fracture toughness at 400°F and 800°F were conducted at the Air Force Wright Aeronautical Materials Laboratory by the Systems Support Division's Engineering and Design Data Group (AFWAL/MLSE).

SECTION II

MATERIALS AND SPECIMENS

The Ti-6Al-4V PM Alloy material for this program was supplied in the form of eight square plain shape blanks 2 1/8" x 2 1/8" x 7/8" thick and fifty-six blanks 9/16" x 9/16" x 3 1/2" long in the sintered and annealed condition. Four of the 2 1/8" square pieces were slabbed in order to provide twice the number of specimen blanks from which crack growth specimens could be machined. The crack growth specimen configuration is shown in Figure 1. The remaining four square blanks were machined into fracture toughness specimens as shown in Figure 2.

Sixteen of the 9/16" x 9/16" x 3 1/2" blanks were machined into tensile specimens shown in Figure 3, and the remaining forty blanks were converted to either smooth or notched fatigue specimens as shown in Figures 4 and 5, respectively.

SECTION III

EQUIPMENT AND PROCEDURE

Chemistry

A chemical analysis of the material was conducted. The results and constituent elements found in the analysis are reported in Table I.

Tensile

The tensile evaluations were conducted on an Instron servohydraulic testing machine suitably equipped for plotting load versus strain recordings at SoRI. Load was sensed by means of a strain-gage load cell and strain was sensed by clip-on extensometers that were attached to mechanical flags located at the specimen gage points. Specimen heating was accomplished by use of a quartz-lamp furnace, which was adjustable vertically in order to regulate temperature gradients in the specimen. Insulation was also used to minimize specimen gradients. The specimens were loaded at approximately 10 KSI per minute.

Operational procedures consisted of installing each specimen in the threaded grips and attaching the grips to the pullrod assembly by insertion of loading pins. The clip-on extensometers were attached on opposite sides of the specimen and the recorder X and Y calibrations were established by switching in the appropriate shunt resistances. The specimen was then loaded at a rate of approximately 10 ksi per minute to failure.

Fatigue

The fatigue specimens were evaluated in both Instron and MTS servohydraulic testing machines. After the machining operation, the diameter of each smooth specimen was measured with a standard micrometer. The notch root diameter of the notched specimens was measured with

a Gaertner traveling microscope and used for calculation of the applied stresses. Each specimen was then installed in the testing machine, and sine-wave cyclic loading was initiated at 25-30 Hz. An R (R = min load/max load) ratio of 0.1 was used for all specimens, and the maximum load for each specimen was selected to fit into the desired range of cycles-to-failure up to a maximum of 1 x 10^7 cycles. Each data point was plotted on semi-log graph paper as the information became available in order to better visualize the curve development and in order to more reasonably estimate the successive load values.

For temperature evaluations, heating was by means of a quartz-lamp furnace at SoRI and an electrical resistance element furnace at AFWAL. Specimen temperature gradients were controlled to acceptable levels when using the quartz-lamps by vertical adjustment of the furnace relative to the specimen and by discreet placement of insulation material as was done for the tensile specimens. For the notched specimens a single thermocouple was wired to the specimen immediately adjacent to the notch. The junction was heat-insulated from direct radiation by the lamps in order to more nearly represent the actual temperature of the specimen. The resistance furnace was a three zone design. Controlling each zone eliminated gradients.

Fatigue Crack Growth Rate

The fatigue crack growth rate studies were conducted in accordance with ASTM E647, "Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} in./Cycle." The constant-load-amplitude cycles were imposed upon the specimens by means of an Instron, Model 1332 servohydraulic testing machine, operating in the frequency range of 5 to 10 Hz at SoRI. Testing at AFWAL/MLSE was accomplished using MTS closed loop servo-hydraulic test equipment for imposition of constant amplitude loading at 30 Hz. Clevis-type grips were used for attachment of each specimen to the pullrod system. Test machines were programmed for sine-wave cyclic

operation, and the load maximum and minimum amplitude monitored by means of a maximum and minimum peak-reading digital voltmeter and also by a built-in oscilloscope. Crack lengths were measured on both sides of the specimen.

For both the precracking and crack-extension procedures, the pre-set counter was adjusted for a predetermined number of cycles. When the intended number of cycles was completed, the machine automatically shut down, thereby permitting careful measurements of the crack length at an exact number of cycles. An electronic counter maintained a running total of the cycle count. Pertinent data was logged at the end of each cycle interval, and the information used to calculate average crack length, average of incremental crack extension, da/dn, and α , or a/W. Each measurement interval was checked against the recommended intervals to assure that the da/dn data were evenly distributed with respect to ΔK. Following are the recommended measurement intervals for CT specimens:

$$\Delta a \leq 0.02W \text{ for } 0.25 \leq a/W \leq 0.60$$
$$\Delta a \leq 0.01W \text{ for } a/W \geq 0.60$$

Additionally, a conscious effort was made to keep α values ≥ 0.2, as was an effort made to keep K_{max} always less than the limiting K_{max} values designated K_{maxL}. Anticipated K_{maxL} values were calculated from known data in conjunction with the a/W versus K_{maxL}/σ_{ys} plot of E647, Figure 6.

For all specimens, precracking stress intensities were selected for crack initiation, followed by a lowering of the stress intensity by no more than 20 percent decrements until a suitable starting level was reached for crack growth. For two specimens, Numbers 1 and 6, the load amplitude was constant throughout the crack growth period. For the remainder of the specimens, incremental changes in load amplitude were effected in order to generate data at different stress intensities than

otherwise would be possible. Appropriate crack extension at each stress intensity preceded each measurement interval.

The secant method was used for calculating the a versus N data. No smoothing method was applied to the crack length data, nor to the calculated results. The N data are considered to be essentially exact, since it was simply a matter of counting the total number of cycles.

Fracture Toughness

The fracture toughness evaluations were conducted in accordance with ASTM E399, "Plane-Strain Fracture Toughness of Metallic Materials." Both the precracking and the load-to-failure operations were performed at room temperature using the same equipment as previously described in the crack growth rate studies. Also, the same grip and pullrod assembly was used, except that different specimen thicknesses required that a different set of spacers be used for specimen centering. Precracking was accomplished by utilizing constant amplitude cyclic loading, keeping in mind the criteria that determine the validity of the test results. A Gaertner traveling microscope and a Pentax microscope were used in monitoring the crack growth in relation to the two lightly scribed marks that denoted maximum and minimum crack lengths.

After precracking, a pair of calibrated clip-on extensometers were attached to the small pins that were located along the hole centerline on each side of the specimen. A uniform loading rate was used to load the specimen while plotting a load versus displacement curve on an autographic recorder. Calibrations were noted on the X-Y chart, and the 0.95 $(P/\delta)_0$ line where $(P/\delta)_0$ is the slope of the line tangent to the initial linear part of the record was drawn from the origin through the curve thus establishing point P_Q at the intercept. The ratio P_{max}/P_Q was calculated to determine if the ratio was within the acceptable limit of 1.10.

If the calculated result was less than both the specimen thickness and the crack length, then K_Q was equal to K_{IC}. Otherwise, the test was an invalid K_{IC} test.

Additionally, the specimen strength ratio, R_{sc}, was calculated as follows:

$$R_{sc} = \frac{2P_{max}(2W + a)}{B(W - a)^2 \sigma_{ys}}$$

where
P_{max} = maximum load, klbf
B = specimen thickness, in.
W = specimen width, in.
a = crack length from crack tip to hole centerline, in.
σ_{ys} = tensile offset yield strength, ksi

SECTION IV

RESULTS AND DISCUSSION

Tensile

A tabulation of the tensile results is presented in Table 2, and the results at each temperature are plotted in Figure 6, 7 and 8. Physical data for all of the cylindrical blanks are given in Table 3. It should be noted that the specific weight values in Table 3 are only approximate since centering holes had already been drilled in the specimen ends when the weights were recorded.

It can be seen from Figure 6 that the ultimate strength decreased from 136.5 ksi at room temperature to 80.2 ksi at 800°F and the yield strength decreased from 122.8 ksi to 63.0 ksi over the same temperature range. The elastic modulus decreased from 17.2 x 10^6 psi to 14.5 x 16^6 psi, Figure 7. The elongation in 1 inch remained nearly constant, varying only from 6 to 7 percent. Also, over the same temperature range of 70 to 800°F, the reduction in area decreased from 26 to 19 percent, Figure 8.

Along with the physical measurements on the tensile specimen blanks, longitudinal and shear velocity measurements were made on a single blank at room temperature by SoRI. The results from the measurements were:

$$V_L = 0.2400 \times 10^6 \text{ in./sec}$$
$$V_S = 0.1254 \times 10^6 \text{ in./sec}$$
$$\rho = 4.386 \text{ g/cc}$$

These values were used to calculate Young's modulus, shear modulus, and Poisson's ratio:

$$E = 16.9 \times 10^6 \text{ psi}$$
$$G = 6.5 \times 10^6 \text{ psi}$$
$$\nu = 0.312$$

The Young's modulus value of 16.9×10^6 psi agrees well with the average value of 17.2×10^6 psi measured in tension.

The calculated results were obtained from the expressions:

$$\nu = \frac{1 - 1/2\left(\frac{V_L}{V_s}\right)^2}{1 - \left(\frac{V_L}{V_s}\right)}$$

$$E = pV_L^2 \frac{(1 + \nu)(1 - 2\nu)}{(1 - \nu)}$$

$$G = V_s^2 p$$

E = Young's modulus, psi

G = shear modulus, psi

ν = Poisson's ratio

V_L = longitudinal velocity, in./sec

V_s = shear velocity, in./sec

$p = w/g$

w = specific weight, lb/in.^{3}

g = gravitational acceleration, 386 in./sec^2

Fatigue

The fatigue results are tabulated in Tables 4 and 5 and are plotted in the graphs of Figures 9 and 10. Figure 9 contains the results at $k_t = 1.0$ (smooth) and Figure 10 at $k_t = 3.0$ for (notched specimens) at the indicated test temperatures.

Figure 9 shows that room temperature specimens cycled at maximum loads from about 74 to 86 ksi, or 60 to 70 percent of yield strength

endured only 45,000 to 50,000 cycles, while one specimen cycled at a maximum load of 70 ksi, or 57 percent of yield strength, endured 1×10^7 cycles without failure. Several specimens tested at very nearly the same stress level failed within a range of cycles from 7.6×10^4 to 2.4×10^6. The shape of the curve indicates that smooth specimens under cyclic maximum loads between 68 and 75 ksi are likely to fail over a broad range of cycles.

Smooth specimens were cycled at 800°F using maximum loads from 95 to 56 percent of the tensile yield strength that was obtained at the same temperature. The resulting data points for the smooth specimens show an orderly increase in cycles on the log scale as the cyclic stress was reduced. The highest stress, 60 ksi, failed the specimen at 3×10^4 cycles, and at the lowest stress, 35 ksi, one specimen failed at 2.5×10^6 cycles, and another at the same stress completed 1×10^7 cycles without failure.

As seen in Figure 10 the 70°F notched-specimen results indicated little scatter in the data between 70 and 34 ksi maximum loads with the number of cycles varying between 4.2×10^3 and 8.6×10^4. All four specimens that were cycled at loads of 32.5 ksi and below endured 1×10^7 cycles without failure.

The notched specimens that were evaluated at 800°F showed the widest scatter in the number of cycles completed versus stress levels. The range of maximum stresses selected for this group was from 35 ksi to 15 ksi, representing 56 and 24 percent of the yield strength at 800°F. The three highest stresses, 35, 30, and 25 ksi, showed a straight-line increase in cycles-to-failure of 2.28×10^4, 5.30×10^4 and 1.12×10^5, respectively, as can be seen on the semi-log plot. However, at stresses of 22 ksi and below, extremely wide scatter was experienced, ranging from 1.72×10^4 to run-out at 1×10^7 cycles without failure. Equipment and procedures were checked at that time in order to learn if a reason could be found for the scatter. No explanation was forthcoming.

Crack Growth Rate

Tabulated results from the six crack growth specimens are presented in Table 6. Specimens numbered 1 and 6 were cycled without change in their constant load amplitude throughout the test. However, the remainder of the specimens were subjected to incremental load amplitude changes in order to expand the number of data points for the limited number of specimens available.

Room temperature crack growth rate results are plotted in Figure 11. No smoothing of the results was attempted, neither from the standpoint of crack length measurements nor the final Δ k values in order to show the scatter. Other than for the amount of actual scatter in the material, the experimental error in making the crack length measurements probably contributed the most toward the scatter. By contrast, the cycle count for each increment of crack length was considered highly accurate, and the load amplitude control was considered to be within 1 percent. Variations in the material could result from a combination of factors such as microstructure, strength, and texture. Point-to-point material variability could exist due to minor processing and material inhomogeneities.

It can be seen in the logarithmic plot of crack growth per cycle, da/dN, versus the stress-intensity factor range for each cycle, Δ k, that the upper region of the plot shows a rapid, unstable crack growth rate starting at a Δ k value of about 32 ksi$\cdot$in.$^{1/2}$. This value corresponds roughly to the K_{IC} values obtained for this material and described in the fracture toughness section of this report.

The crack growth data measured at AFWAL/MLSE at 400°F and 800°F are shown in Figures 12 and 13. The data are represented by straight lines on Figure 11.

Fracture Toughness

Of the four fracture toughness specimens available for room temperature testing only two of the specimens were successfully carried beyond the precracking stage.

Table 7 gives a tabulation of measured and calculated data for these two specimens. Both specimens revealed typical fracture surfaces for PM materials in that the surfaces were essentially flat, with slight fraction oblique edges.

Fracture toughness data was measured by AFWAL at 400°F and 800°F. Data reduced from those tests may be found in Table 8.

SECTION V

COMPARISON

Tensile

The mechanical properties generated from room temperature tensile tests were equivalent to those shown for annealed sheet, strip, and plate in Reference 1, and beta-annealed "low oxygen" processed plate in Reference 5. Tensile ultimate and yield strengths were again equivalent at 400°F and 800°F to those shown in Reference 5. Modulus of Elasticity values for the PM "Elemental Blend" material tested in this effort were also equivalent. Tensile properties were superior to those shown for other PM prealloyed material in References 3, 5, 6. Tensile ultimate and yield strengths were higher and modulus values equal to those in Reference 4.

Fatigue

Fatigue data generated for smooth and notched specimens was not as good as that shown for wrought material in the annealed condition in Reference 1 or 5. However, when compared to other PM products this material performed better than the material tested in Reference 6 and equivalent to that in Reference 3 and 5. When compared with fatigue behavior of other blended elemental and prealloyed material to ingot material in Reference 9, this data falls along the lower boundary for wrought Ti-6Al-4V and the upper side of the blended elemental. Data from prealloyed powder compacts as shown was slightly higher. See Figure 11.

Fatigue Crack Growth Rate

Fatigue Crack Growth rates were also investigated in laboratory air at room temperature, 400°F and 800°F. Crack growth rates were similar to those shown in Reference 1 and 10 but faster than those found in Reference 2, 3, and 7.

A comparison from Reference 10 is included to illustrate fatigue crack growth rates for prealloyed powder metallurgy consolidated material and wrought annealed Ti-6Al-4V. See Figure 13.

Fracture Toughness

Fracture toughness values at room temperature were significantly less than those shown in References 2 and 7 and approximately equivalent to those of Reference 3. It should be noted that the wrought (annealed) products used in this comparison took many forms including forgings and various thicknesses of rolled plate.

No stress rupture or stress corrosion data was generated in this effort.

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TABLE 1

Chemical Analysis of PM Ti-6Al-4V Material

Two Readings		
5.76 - 6.01%	Al	(by weight)
3.84 - 3.93%	V	
0.18 - 0.19%	Fe	
0.11 - 0.12%	Cl	
Balance	Ti	

Trace Elements

150 PPM	Si
50	Mg
50	Mn
10	B
20	Sn
20	Ph
150	Ni
25	Cu
50	Cr
100	W
5	Ca
10	Mo
20	Zr
100	Co

TABLE 2

TENSILE PROPERTIES OF PM Ti-6Al-4V MATERIAL AT
ROOM TEMPERATURE AND ELEVATED TEMPERATURE

Specimen Number	Temperature °F	Ult. Tensile Strength ksi	0.2% Offset Yield Strength ksi	Elasticity 10^6 psi	Elongation in 1 inch %	Reduction in Area %
1	70	137.1	122.9	17.2	7	26
2	70	136.3	123.0	16.9	7	25
3	70	136.0	123.0	17.2	7	25
4	70	136.2	122.2	17.1	7	27
5	70	137.0	123.0	17.5	7	27
	Avg	136.5	122.8	17.2	7	26
6	400	104.0	85.8	16.9	7	18
7	400	104.8	86.4	15.8	7	20
8	400	104.8	86.9	16.7	6	19
9	400	105.3	87.4	17.3	7	31
10	400	105.0	87.7	16.5	7	29
	Avg	104.8	86.8	16.6	7	23.4
11	800	81.4	65.6[1]	15.4	6	15
12	800	79.4	62.2	14.1	7	23
13	800	79.8	63.4	14.4	6	19
14	800	80.5	63.5	14.4	7	18
15	800	80.8	63.2	14.9	7	24
16	800	79.4	62.7	14.0	6	15
	Avg	80.2	63.0[2]	14.5	6	19

[1] Possible extensometer flag slippage near yield point resulted in uncertainty of yield data

[2] Does not include yield data for Specimen Number 11

TABLE 3

PHYSICAL DATA FOR PM Ti-6Al-4V SPECIMEN BLANKS

Specimen Number	Dimensions Inches		Weight	Specific Weight
	Diameter	Length	gm	gm/cm^3
1	0.500	3.094	43.4506	4.362
2	0.500	3.092	43.4074	4.371
3	0.500	3.092	43.4589	4.366
4	0.500	3.092	43.4474	4.365
5	0.500	3.093	43.5734	4.376
6	0.500	3.093	43.5320	4.372
7	0.500	3.093	43.4265	4.361
8	0.500	3.093	43.4049	4.359
9	0.500	3.093	43.4618	4.365
10	0.500	3.091	43.3474	4.356
11	0.500	3.092	43.2464	4.345
12	-	-	43.8782	-[2]
13	0.500	3.092	43.5878	4.379
14	0.500	3.091	43.4375	4.366
15	0.500	3.091	43.5989	4.382
16	0.500	3.092	43.2758	4.348

[1]Specific weight is approximate since centering holes had already been drilled.

[2]Data not available due to irregular shape of blank.

TABLE 4

Fatigue Data[1] for Smooth Specimens of Ti-6Al-4V at Room Temperature, 400°F, and 800°F in Air

Specimen Number	Temperature °F	Max. Stress ksi	Cycles to Failure
10	70	68.5	542,400
2	70	70.0	10,525,550
9	70	71.0	75,700
8	70	72.0	307,500
4	70	73.0	2,400,100
7	70	73.5	47,100
5	70	74.0	48,100
3	70	76.0	80,100
1	70	80.0	40,530
6	70	85.0	44,780
3	400	50	453,500
4	400	50	>11,356,700
10	400	57.5	>10,921,000
1	400	60	4,732,100
2	400	60	8,873,100
7	400	65	7,824,600
9	400	67.5	5,463,200
5	400	70	2,646,600
8	400	70	106,300
6	400	75	67,400
16	800	35.0	2,611,700
18	800	35.0	>10,000,000
14	800	38.0	4,354,900
19	800	38.0	6,800,000
13	800	40.0	3,953,700
12	800	42.0	4,347,300
11	800	44.0	1,426,400
15	800	50.0	306,100
17	800	56.0	171,000
20	800	60.0	29,100

[1] 30 Hz; R=0.1

TABLE 5

Fatigue Data[1] for Notched Specimens of
Ti-6Al-4V at Room Temperature, 400°F, and 800°F in Air

Specimen Number	Temperature °F	Max. Stress ksi	Cycles to Failure
5	70	25.0	>10,000,000
6	70	30.0	>10,000,000
9	70	31.0	>10,000,000
10	70	32.5	>10,000,000
7	70	34.0	55,800
8	70	34.0	86,100
4	70	40.0	38,300
3	70	50.0	22,100
2	70	60.0	8,900
1	70	70.0	4,200
16	400	20	>11,249,400
20	400	25	431,900
19	400	30	93,700
18	400	40	24,900
17	400	50	11,400
13	400	60	16,500
17	800	15.0	>10,000,000
15	800	17.0	290,000
16	800	17.0	17,200
18	800	18.0	>10,000,000
11	800	20.0	8,172,200
20	800	20.0	45,600
14	800	22.0	6,948,800
12	800	25.0	112,100
13	800	30.0	53,000
19	800	35.0	22,800

[1] 30 Hz; R = 0.1

TABLE 6

TABULATED DATA FOR SIX Ti-6Al-4V CRACK GROWTH RATE SPECIMENS[1,2]

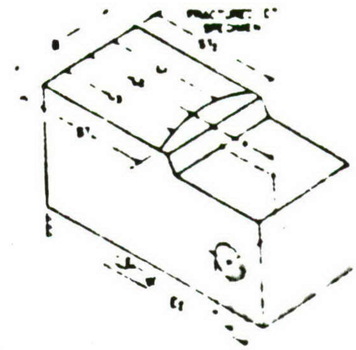
SORI Room Temperature

Specimen[3] Number	P_{max} lb	ΔP[4] lb	Number of Cycles	Average Crack Length Within Increment a inches	Crack Increment inches	K_{max} ksi · in.$^{1/2}$	ΔK ksi · in.$^{1/2}$	$\Delta a/dN$
1-1	760	684	1,710	0.658	0.015	15.0	13.5	8.7×10^{-6}
1-2	760	684	1,800	0.685	0.014	15.7	14.1	7.7×10^{-6}
1-3	760	684	1,760	0.774	0.023	18.6	16.7	1.3×10^{-5}
1-4	760	684	1,780	0.804	0.037	19.4	17.5	2.1×10^{-5}
1-5	760	684	1,790	0.876	0.037	22.7	20.4	2.1×10^{-5}
1-6	760	684	1,770	0.925	0.060	25.3	22.8	3.4×10^{-5}
1-7	760	684	1,500	1.002	0.095	30.4	27.4	6.3×10^{-5}
2-1	600	540	3,000	0.643	0.014	11.6	10.4	4.7×10^{-6}
2-2	600	540	3,000	0.656	0.011	11.8	10.6	3.7×10^{-6}
2-3	600	540	3,000	0.665	0.007	12.0	10.8	2.3×10^{-6}
2-4	600	540	3,000	0.674	0.011	12.2	11.0	3.7×10^{-6}
2-5	700	630	3,000	0.694	0.014	14.8	13.3	4.7×10^{-6}
2-6	700	630	3,000	0.737	0.022	15.9	14.3	7.3×10^{-6}
2-7	800	720	3,000	0.780	0.043	19.7	17.7	1.4×10^{-5}
2-8	800	720	3,000	0.827	0.052	21.6	19.4	1.7×10^{-5}
2-9	900	810	1,000	0.914	0.043	29.1	26.2	4.3×10^{-5}
2-10	900	810	1,000	0.977	0.084	33.9	30.5	8.4×10^{-5}
3-2	800	720	3,000	0.540	0.011	13.1	11.8	3.7×10^{-6}
3-3	800	720	3,000	0.554	0.017	13.3	12.0	5.7×10^{-6}
3-4	900	810	3,000	0.578	0.020	15.6	14.0	6.7×10^{-6}
3-5	900	810	3,000	0.600	0.023	16.2	14.6	7.7×10^{-5}
3-6	900	810	3,000	0.627	0.032	16.9	15.2	1.1×10^{-5}
3-7	1000	900	3,000	0.670	0.042	20.2	18.2	1.4×10^{-5}
3-8	1000	990	3,000	0.717	0.052	24.1	21.7	1.7×10^{-5}
4-1	950	855	5,000	0.537	0.046	15.6	14.0	9.2×10^{-6}
4-2	1050	945	3,000	0.581	0.017	18.2	16.4	5.7×10^{-6}
4-3	1050	945	4,000	0.618	0.058	19.4	17.5	1.4×10^{-5}
4-4	1150	1035	2,000	0.690	0.044	24.1	21.7	2.2×10^{-5}
4-5	1250	1125	1,000	0.745	0.038	28.8	25.9	3.8×10^{-5}
4-6	1250	1125	1,000	0.802	0.076	31.9	28.7	7.6×10^{-5}
5-1	1200	1080	5,300	0.551	0.082	20.0	18.0	1.6×10^{-5}
5-2	1350	1215	2,000	0.631	0.056	25.4	22.9	2.8×10^{-5}
6-1	1500	1350	2,500	0.542	0.071	24.1	21.7	2.8×19^{-5}
6-2	1500	1350	1,500	0.606	0.058	27.3	24.6	3.9×10^{-5}
6-3	1500	1350	1,000	0.658	0.044	29.8	26.8	4.4×10^{-5}
6-4	1500	1350	700	0.704	0.048	32.0	28.8	6.8×10^{-5}
6-5	1500	1350	300	0.740	0.024	34.0	30.6	8.0×10^{-5}
6-6	1500	1350	150	0.765	0.026	35.9	32.3	1.7×10^{-4}
6-7	1500	1350	100	0.787	0.018	37.3	33.6	1.8×10^{-4}
6-8	1500	1350	85	0.814	0.035	39.2	35.3	4.1×10^{-4}
6-9	1500	1350	33	0.850	0.037	41.8	37.6	1.1×10^{-3}

1. All specimens loaded with R = 0.1 and at a frequence of 5 Hz, sinwave.
2. Tensile 0.2% offset yield strength at room temperature was 122.8 ksi.
3. "Dash" number indicates measurement sequence.
4. In all cases, initial ΔP was the same as the terminal ΔP for precracking.

TABLE 7

MEASURED AND CALCULATED K_{IC} DATA FOR TWO Ti-6Al-4V PM ALLOY SPECIMENS (SORI)



FRACTURE TOUGHNESS K_{IC} DATA SHEET

MATERIAL Ti-6Al-4V PM Alloy

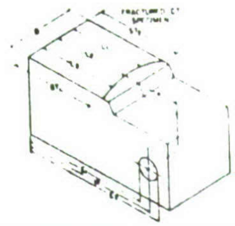
SPECIMEN NO. 2 and 4

DATE

SPECIMEN NO.	2	4
FATIGUE PRECRACK		
P_C FINAL MAX. LOAD (LBS)	1,200	1,000
FINAL CYCLES	10,000	10,000
TEST TEMPERATURE °F	70	70
SPECIMEN DIMENSIONS		
B (IN.)	0.800	0.800
E_1 (IN.)	1.410	1.410
E_2 (IN.)	1.790	1.790
$W = E_1 + E_2/2$ (IN.)	1.600	1.600
L_1 (IN.)	0.673	0.720
L_2 (IN.)	0.644	0.682
L_3 (IN.)	0.655	0.673
L AVG. = $L_1 + L_2 + L_3/3$ (IN.)	0.657	0.692
a = W-L AVG. (IN.)	0.943	0.908
ST_1 (IN.)	0.662	0.725
ST_2 (IN.)	0.710	0.708
TEST RECORD		
P_Q (LBS)	2,990	2,900
PMAX (LBS)	3,010	3,050
TEST TEMPERATURE (°F)	70	70
CALCULATION		
a/W (.45-.55)	0.59	0.57
f(a/W) =	12.7	12.02
$K_Q = P_Q \times F(a/W)/B\sqrt{W}$ (KSI$\sqrt{IN.}$)	37.5	34.4
$PMAX/P_Q$ = (<1.10)	1.007	1.05
RSI	0.586	0.536
ORIENTATION		
YIELD STRENGTH (KSI)	122.8	122.8
$2.5\,(K_Q/Y.S.)^2$ (IN.) <B;a	0.23 < 0.8 .94	0.20 < .8 + .91
ST_1/L,AVG.<1.1	1.01	1.05
ST_2/L,AVG.<1.1	1.08	1.02
P_f/P_C <0.6		
L_1/L_2, L_2/L_3, L_3/L_1 = .95 - 1.05	1.04,0.98,0.97	1.06,1.01,1.01
Y.S. @ 400°F 86.8		
Y.S @ 800°F 63.0		
VALID K_{IC} TEST?	A/W = 0.59	A/W = 0.57

FRACTURE TOUGHNESS K_{IC} DATA SHEET

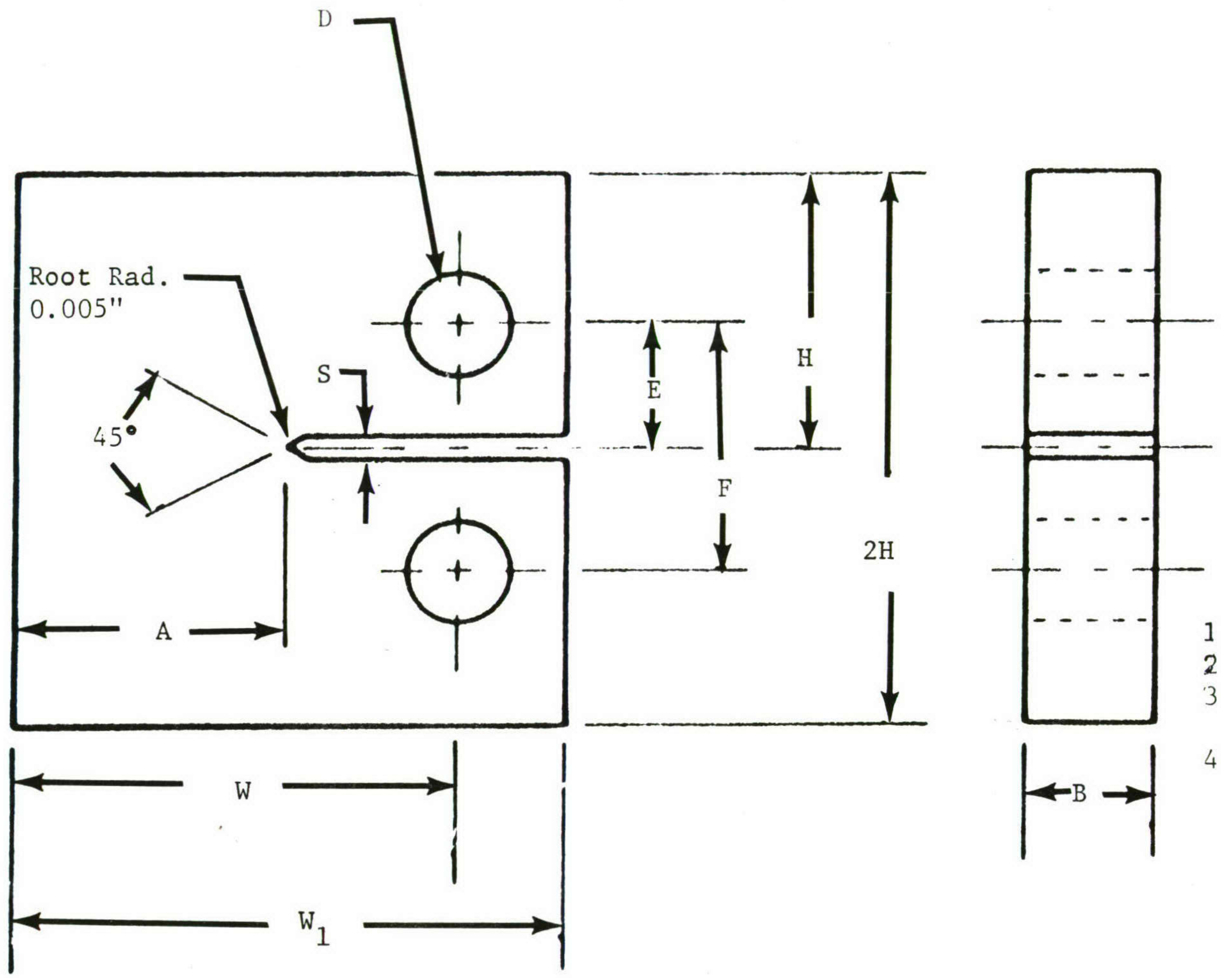
Table 8
(AFWAL MLSE)



ALLOY	Titanium	HEAT TREAT.	6-4 pm
FORM		PROJECT ENGR.	Neal Ontko
DATE	Nov. 1983	TECHNICIAN	MACHINE USED
FATIGUE CRACK		John Eblin	4 Post MTS
TESTED		John Eblin	Tinius Olsen

SPECIMEN NO.	1	2	3	4	5	6
FATIGUE PRECRACK						
P_Q FINAL MAX. LOAD (LBS.)	1300	1100	1000	1100	1250	1250
FINAL CYCLES	50,000	40,000	13,000	60,000	45,000	45,000
TEST TEMPERATURE °F	400	400	400	800	800	800
SPECIMENS DIMENSIONS						
B (IN.)	.8021	.8023	.8024	.8023	.8021	.8020
E_1 (IN.)	1.4101	1.4097	1.4110	1.4115	1.4111	1.4115
E_2 (IN.)	1.7904	1.7907	1.7909	1.7919	1.7910	1.7930
$W = E_1 + E_2/2$ (IN.)	1.6003	1.6002	1.6010	1.1017	1.6011	1.6023
L_1 (IN.)	.7593	.7776	.7693	.7788	.7746	.7488
L_2 (IN.)	.7547	.7503	.7544	.7597	.7633	.7393
L_3 (IN.)	.7711	.7632	.7629	.7710	.7697	.7572
L AVG. + $L_1 + L_2 + L_3/3$ (IN.)	.7617	.7637	.7622	.7698	.7692	.7484
a = W-L AVG. (IN.)	.8386	.8370	.8390	.8320	.8320	.854
ST_1 (IN.)	.7964	.8120	.8231	.8113	.8126	.8026
ST_2 (IN.)	.8112	.7942	.8109	.8114	.8135	.8010
TEST RECORD						
P_Q (LBS.)	4230	4150	4120	3660	3720	3630
PMAX (LBS.)	4240	4150	4120	3950	4020	3930
TEST TEMP. (°F)	400	400	400	800	800	800
CALCULATIONS						
a/w [.45-.55]						
f(a/w) =						
$K_Q = P_Q \times f(a/w)/B\sqrt{W}$ (KSI$\sqrt{IN.}$)	43.4	42.5	42.3	37.0	37.7	38.4
$PMAX/P_Q$ = [<1.10]	1.00	1.0	1.0	1.08	1.08	1.08
ORIENTATION						
YIELD STRENGTH (KSI)						
$2.5(K_Q/Y.S.)^2$ (IN.)<B;a	.63<.8021/.839	.60<.802/.837	.59<.802/.839	.86<.802/.832	.90<.802/.832	.93<.802/.854
ST_1/LAVG.<1.1	1.05	1.06	1.08	1.05	1.06	1.07
ST_2/LAVG.<1.1	1.065	1.04	1.06	1.05	1.06	1.07
P_f/P_Q 0.6						
L_1/L_2, L_2 L_3, L_3/L_1 = .95-1.05	1.01,.98,1.02	1.04,.98,.98	1.02,.99,.99	1.01,.99,.99	1.06,.99.99	1.01,.98,1.01
Y.S. @ 400°F 86.8						
Y.S. @ 800°F 63.0						
VALID K_{IC} TEST?	yes	yes	yes	no	no	no
REASON WHY NOT				$2.5(\frac{K}{ys})^2$>B;a	$2.5(\frac{K}{ys})^2$>B;a	$2.5(\frac{K}{ys})^2$>B;a
PRECRACK (LBS.)	x 10^3					
2400/240	9	16	22	15	16	17
1300/130	50					
2300/230		27				
1250/125	20	27	55	45	45	
1100/110	40		60			
1000/100		13				

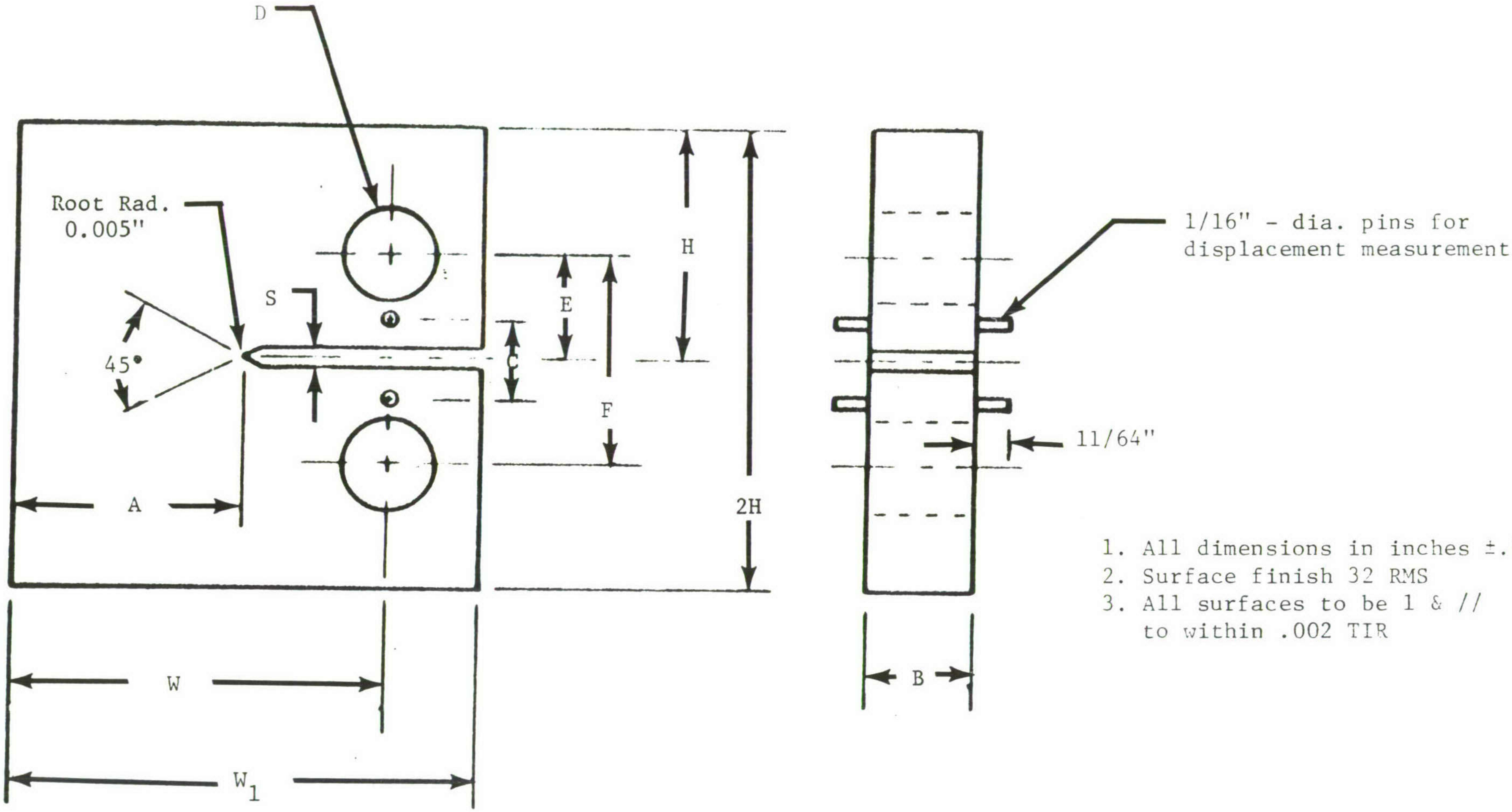
Measured and calculated K_{1C} data for Ti-6Al-4V PM alloy specimen



1. All dimensions in inches ±.003
2. Surface finish 32 RMS
3. All surfaces to be ⊥ & / / to within .002 TIR
4. Note: blocks may be slabbed to produce 2 specimens per 7/8" piece

B	A	W	W_1	S	E	F	H	D
0.300	1.200	1.600	2.000	0.200	0.440	0.880	0.960	0.380

Figure 1. Specimen Configuration for Crack Growth Rate Evaluations



1. All dimensions in inches ±.003
2. Surface finish 32 RMS
3. All surfaces to be ⊥ & //
   to within .002 TIR

B	A	W	W_1	S	E	F	H	D	C
0.800	0.780	1.600	2.000	0.200	0.440	0.880	0.960	0.380	0.360

Figure 2. Specimen Configuration for Fracture Toughness Evaluations

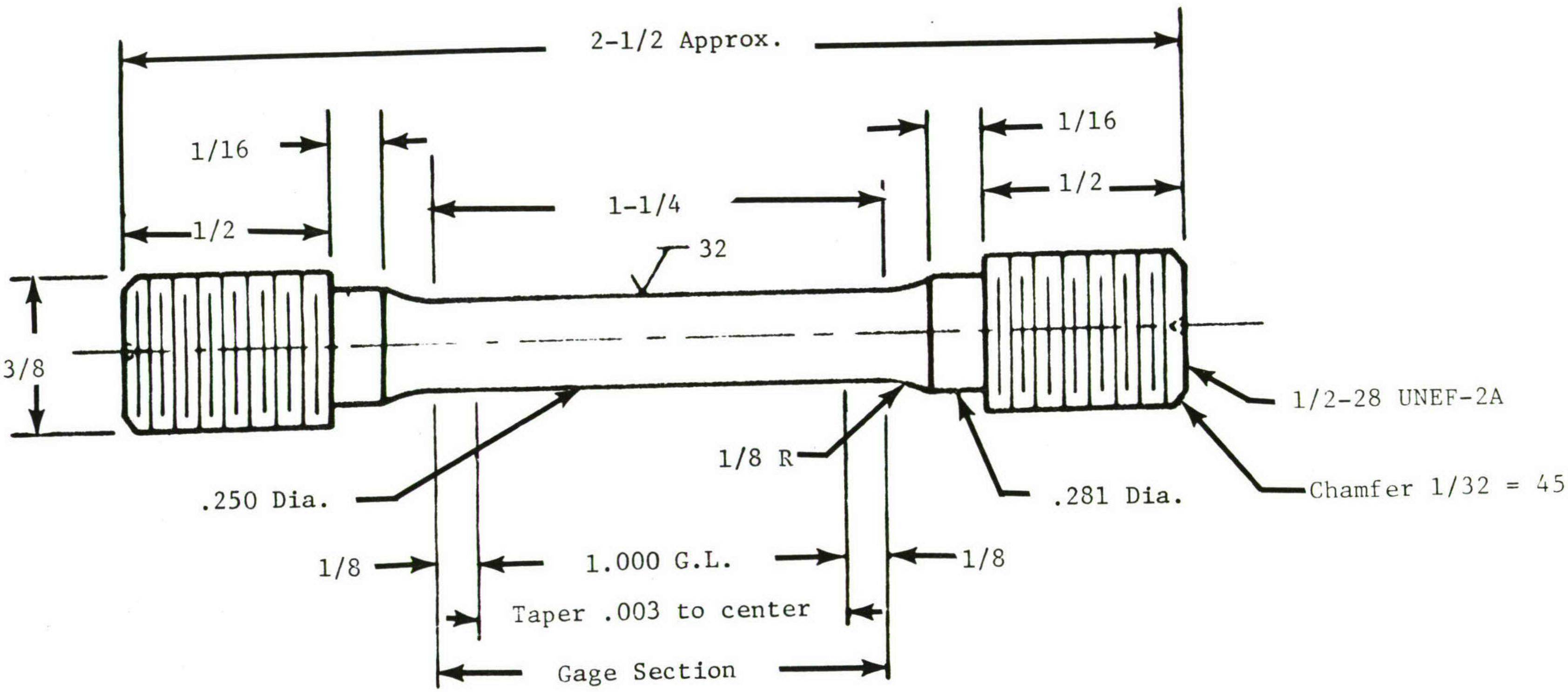
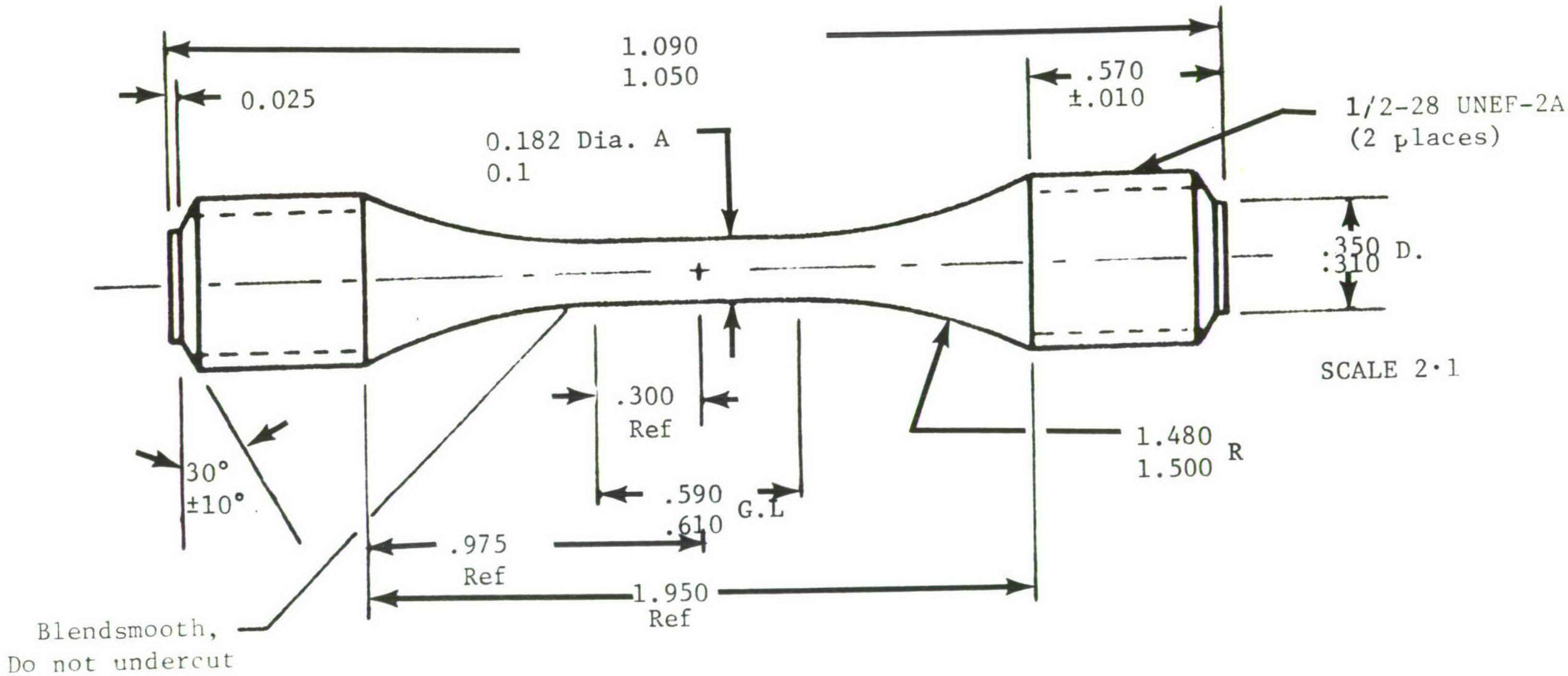
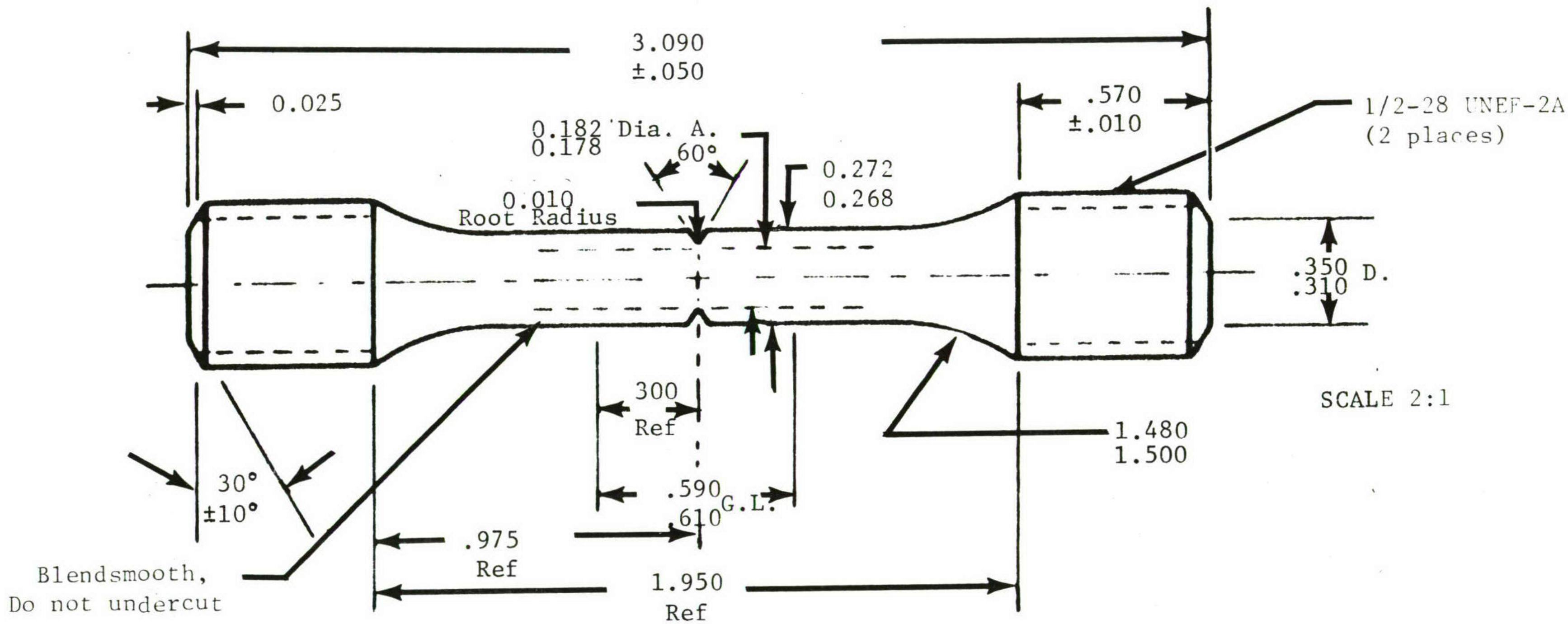


Figure 3. Tensile Specimen



1. Taper gage length (G.L.) .001 from ends to center.
2. Gage length must not be undercut at ends
3. Polish longitudinal--G.L. must be free from circumferential scratches.
4. Center drilling is permitted.

Figure 4. Smooth Fatigue Specimen



1. Root radius 0.010", V notch at 60°
2. Gage length must not be undercut at ends
3. Polish longitudinally--G.L. must be free from circumferential scratches.
4. Center drilling is permitted.

Figure 5. Notched Fatigue Specimen

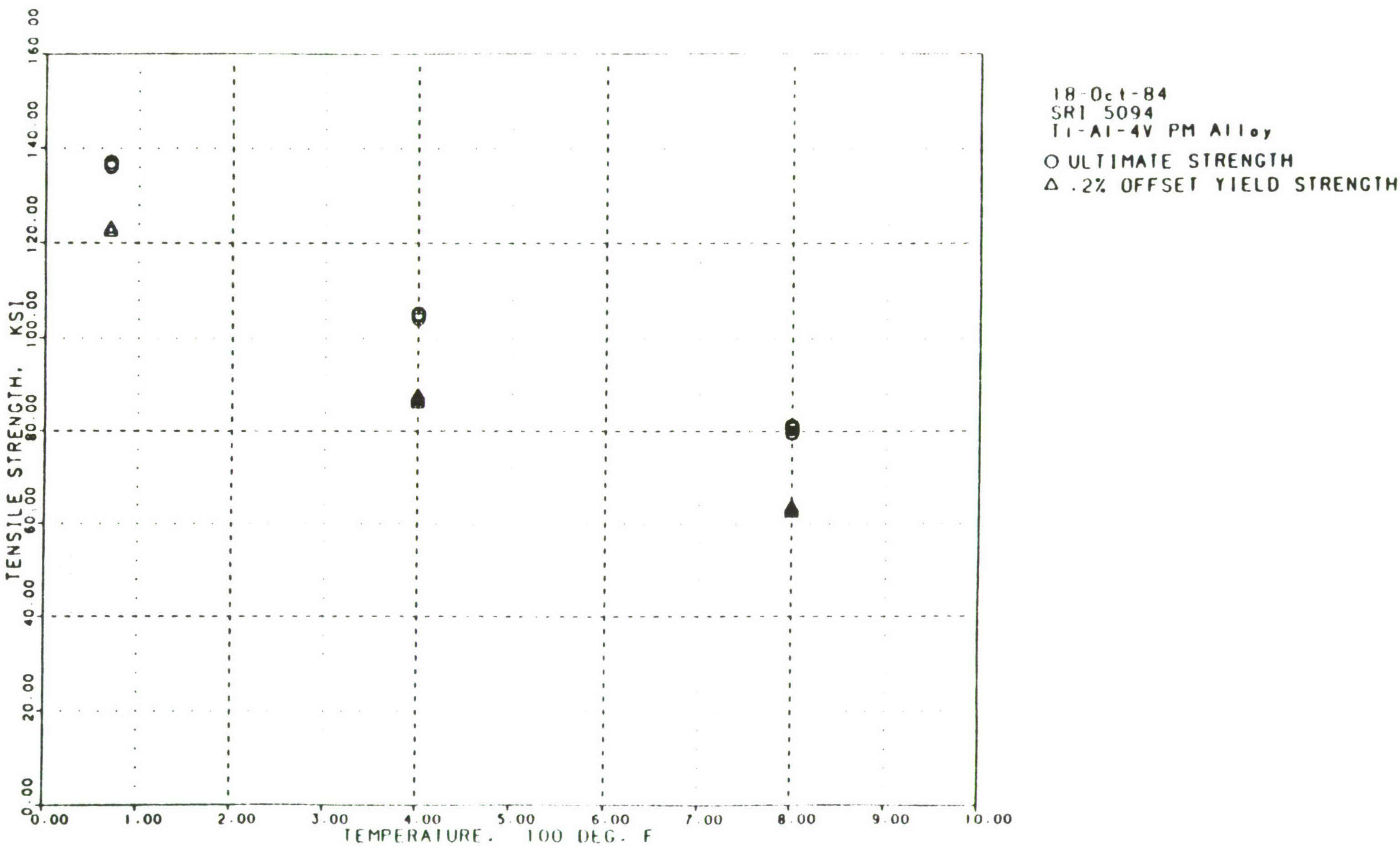


Figure 6. Ultimate Strength & Yield Strength of Tensile Specimens From Ti-6Al-4V PM Alloy

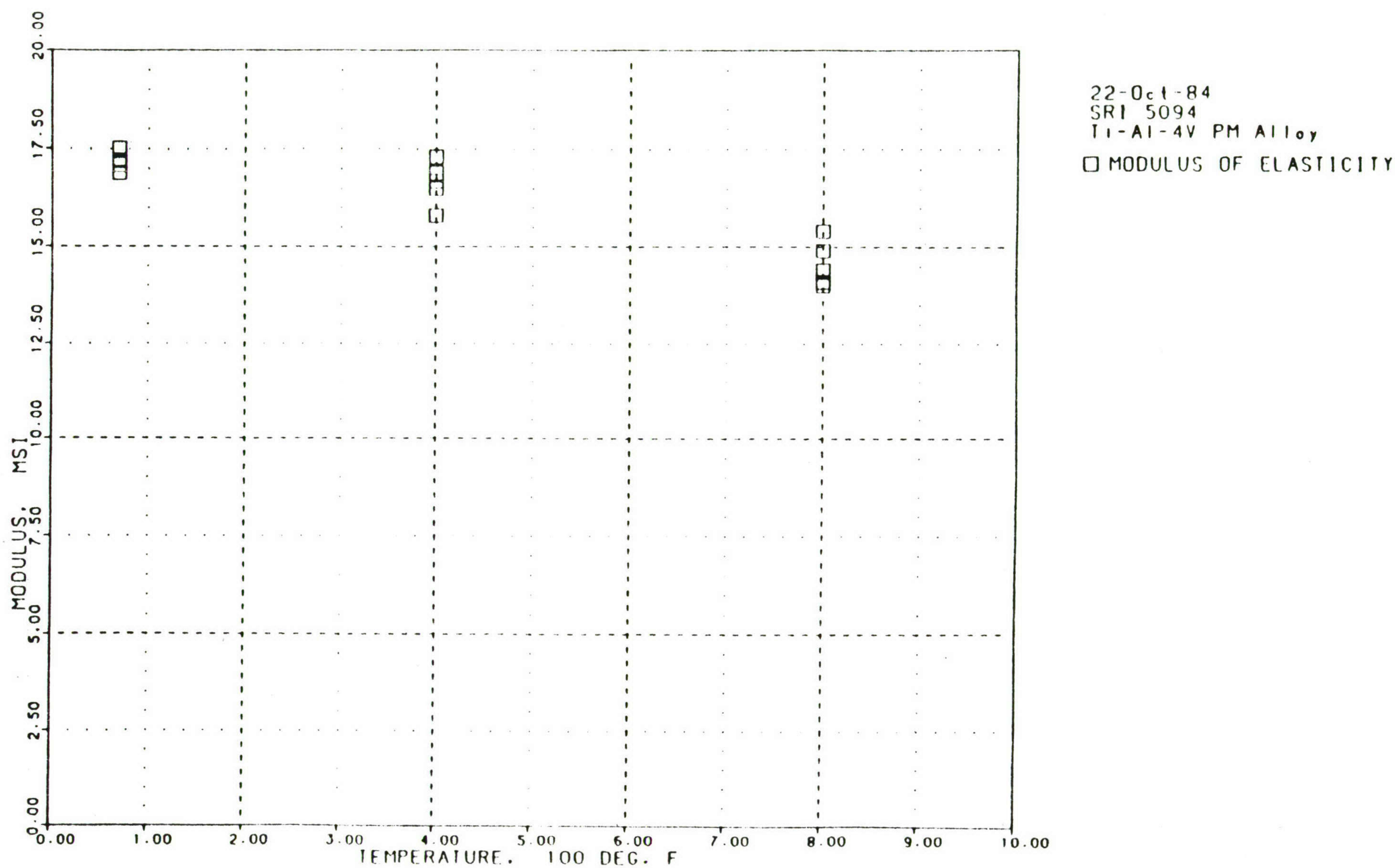


Figure 7. Modulus of Elasticity of Tensile Specimens From Ti-6Al-4V PM Alloy

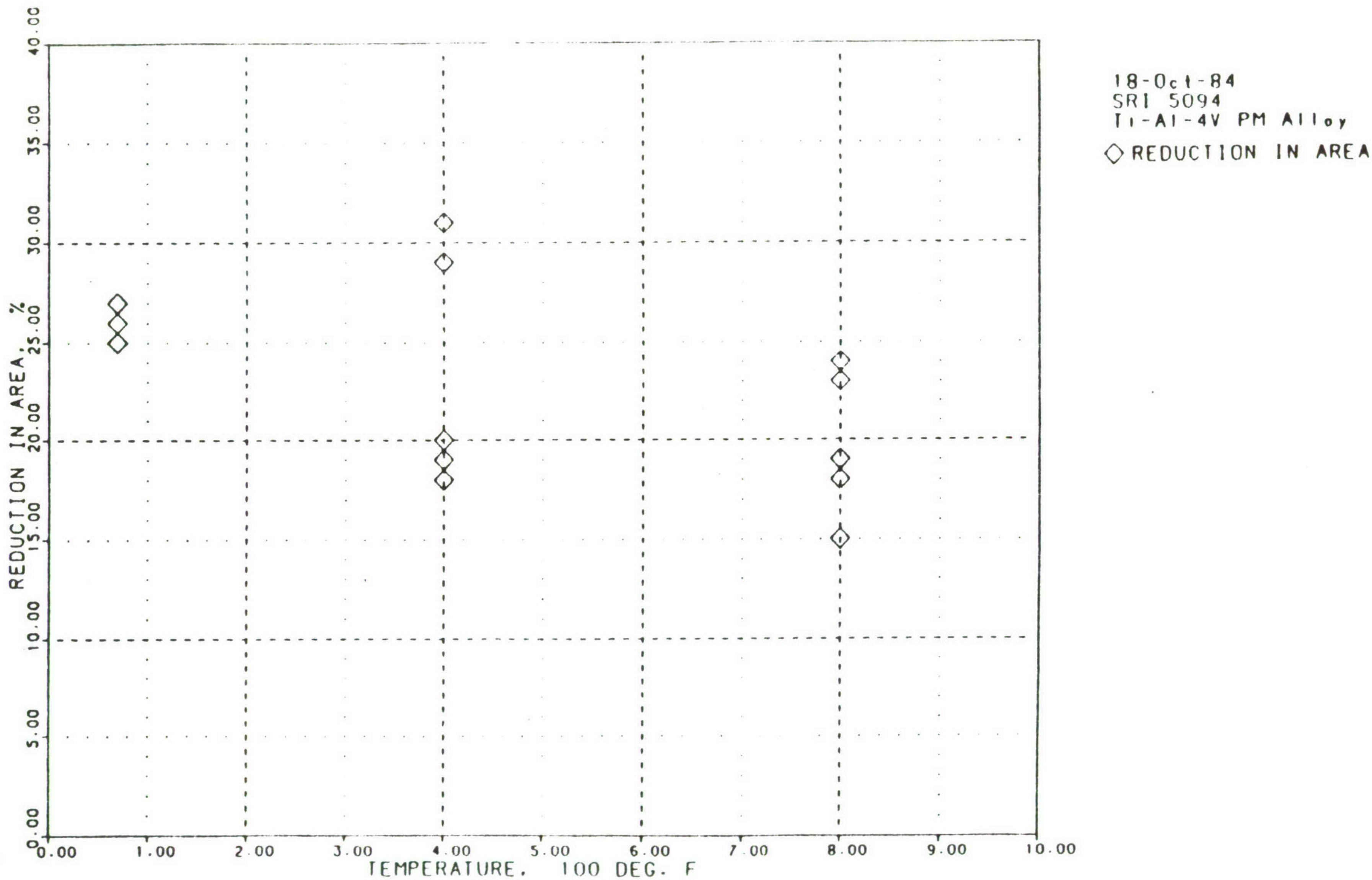


Figure 8. Reduction in Area of Tensile Specimens From Ti-6Al-4V PM Alloy

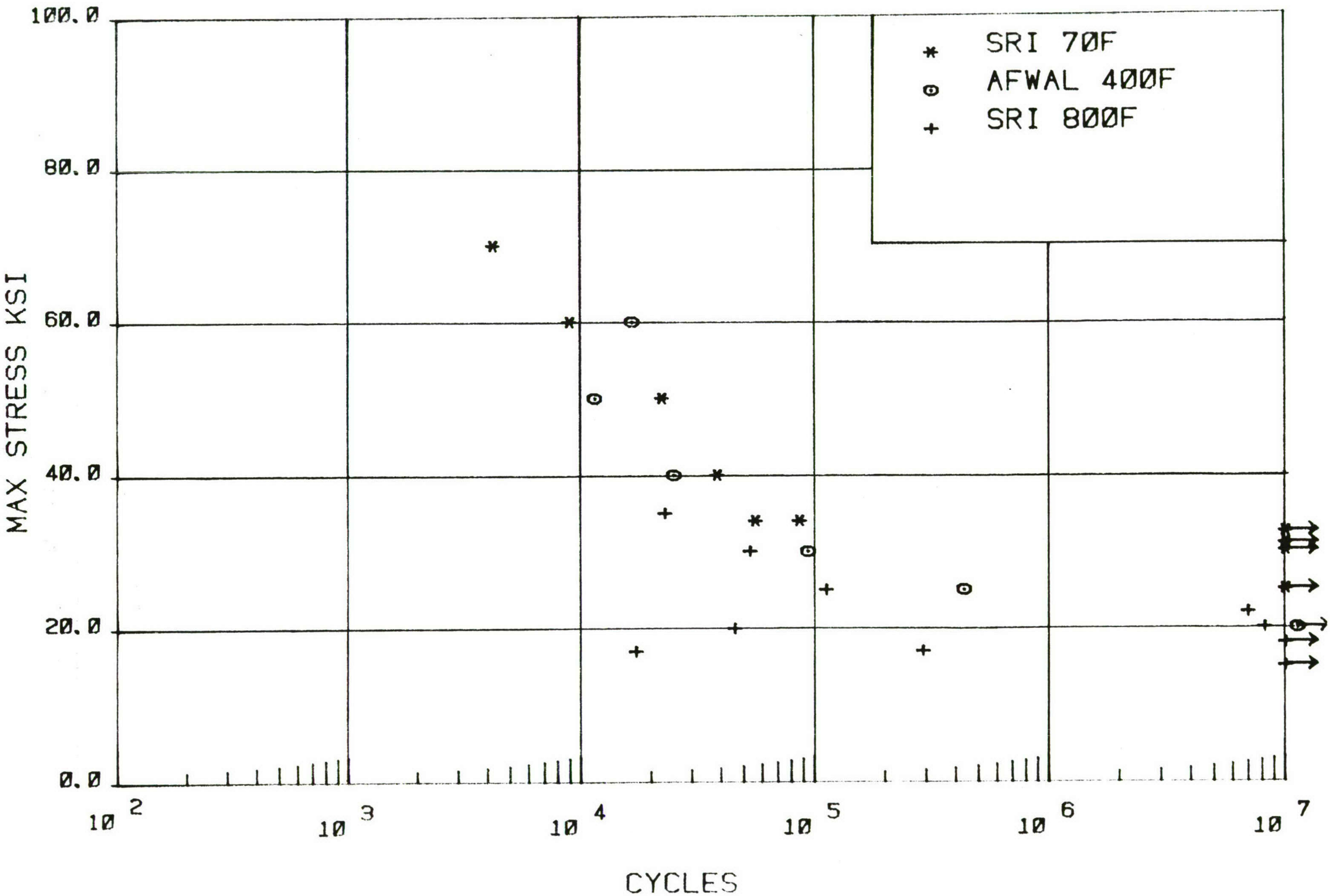


Figure 9. Fatigue Data at 70°, 400°, and 800° for Smooth PM Ti-6Al-4V Specimens

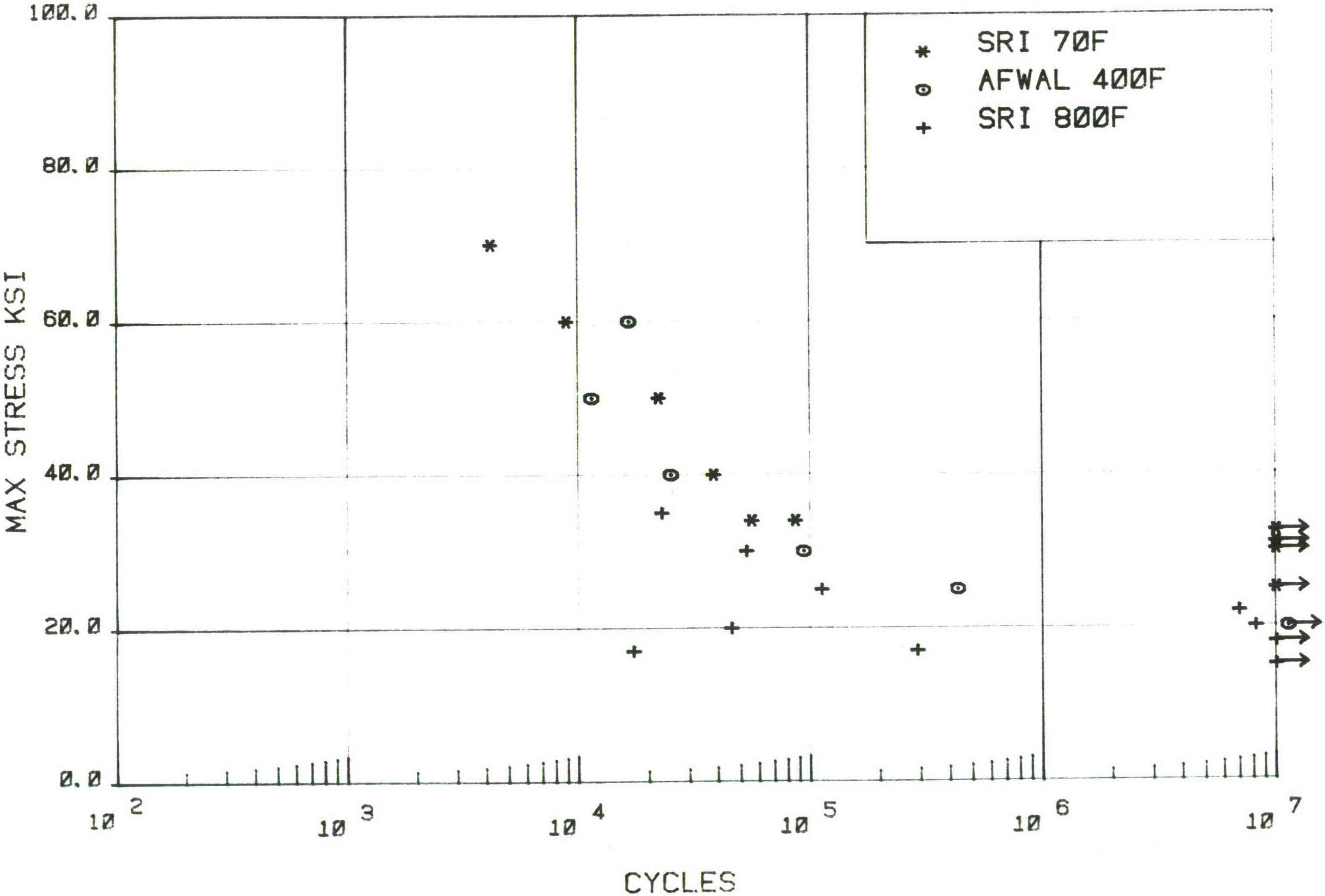


Figure 10. Fatigue Data at 70°, 400°, and 800°F for Notched (K_t = 3.0) PM Ti-6Al-4V Specimens

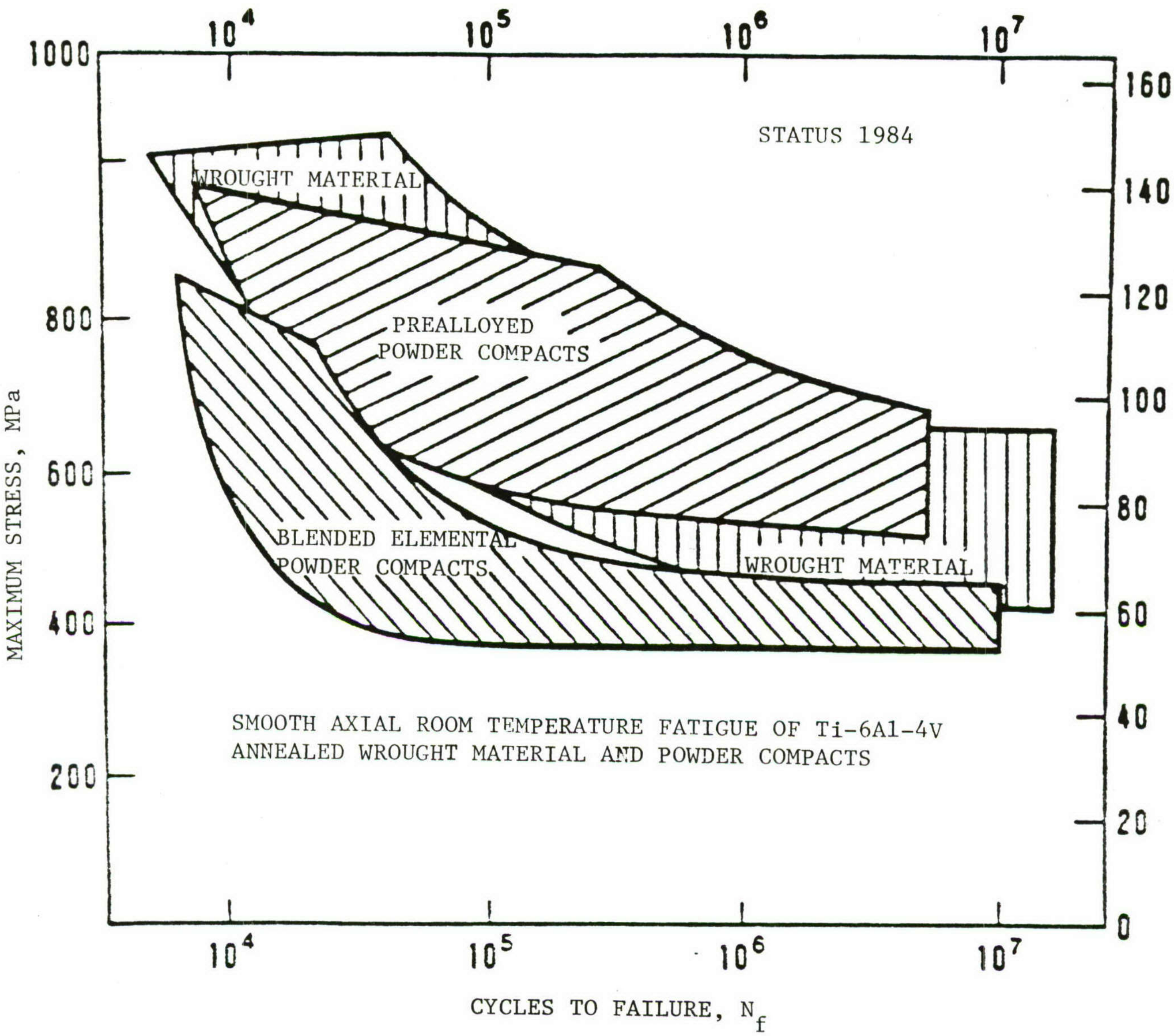


Figure 11. Comparison of Fatigue Behavior of Annealed Blended Elemental and Prealloyed Ti-6Al-4V PM Compacts, with Ingot Metallurgy Material.

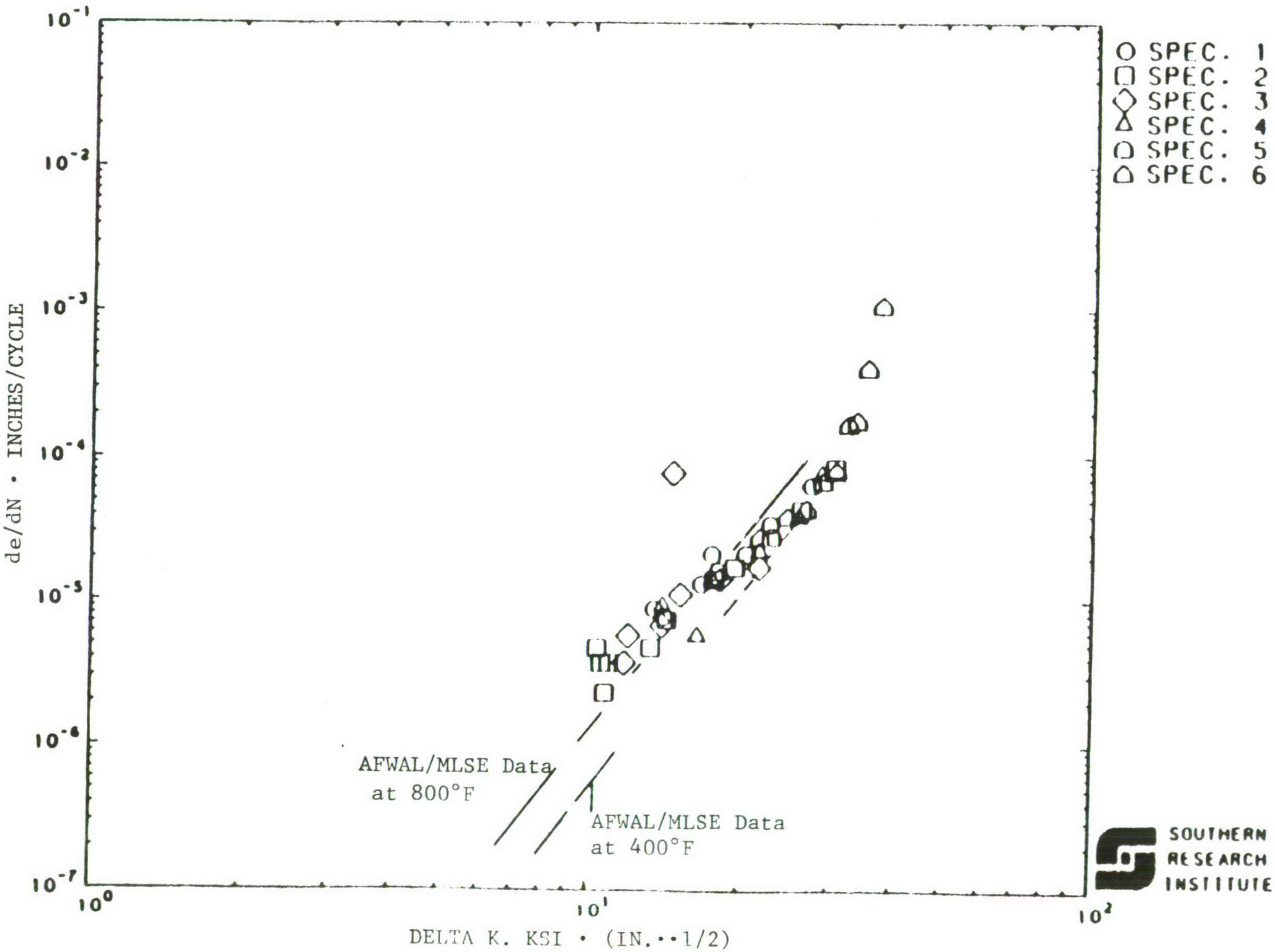


Figure 12. Crack Growth Rate Versus Stress Intensity for PM Ti-6Al-4V Specimens (SORI RT Points Plotted, AFWAL 400° + 800° data shown as Straight Lines)

35

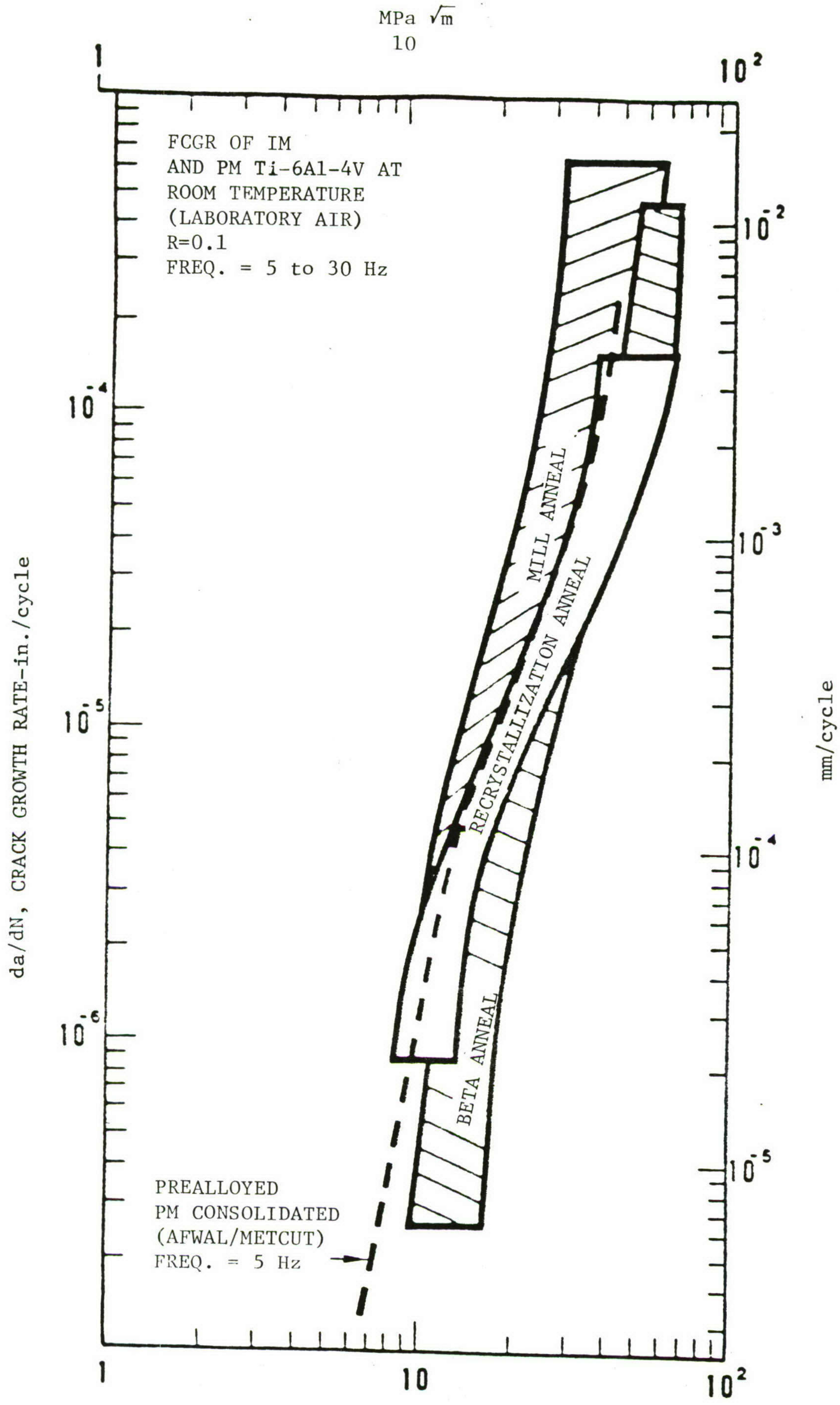


Figure 13. Comparison between FCGR in Powder Matellury Compacts and Ingot Metallurgy Material.

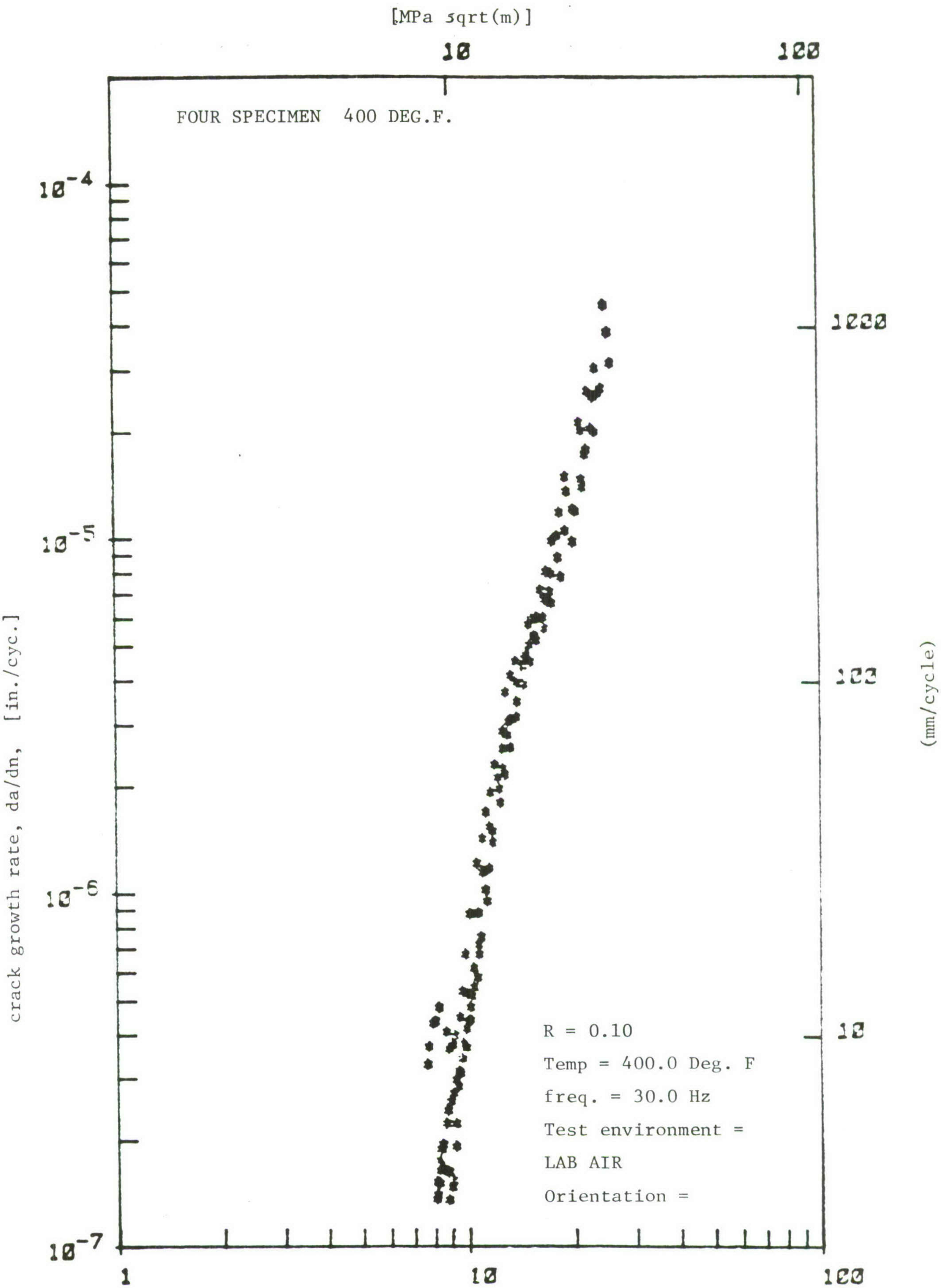


Figure 14. Stress Intensity Range, Delta K, (KSI sqrt [in.)]
AFWAL da/dN @ 400°F

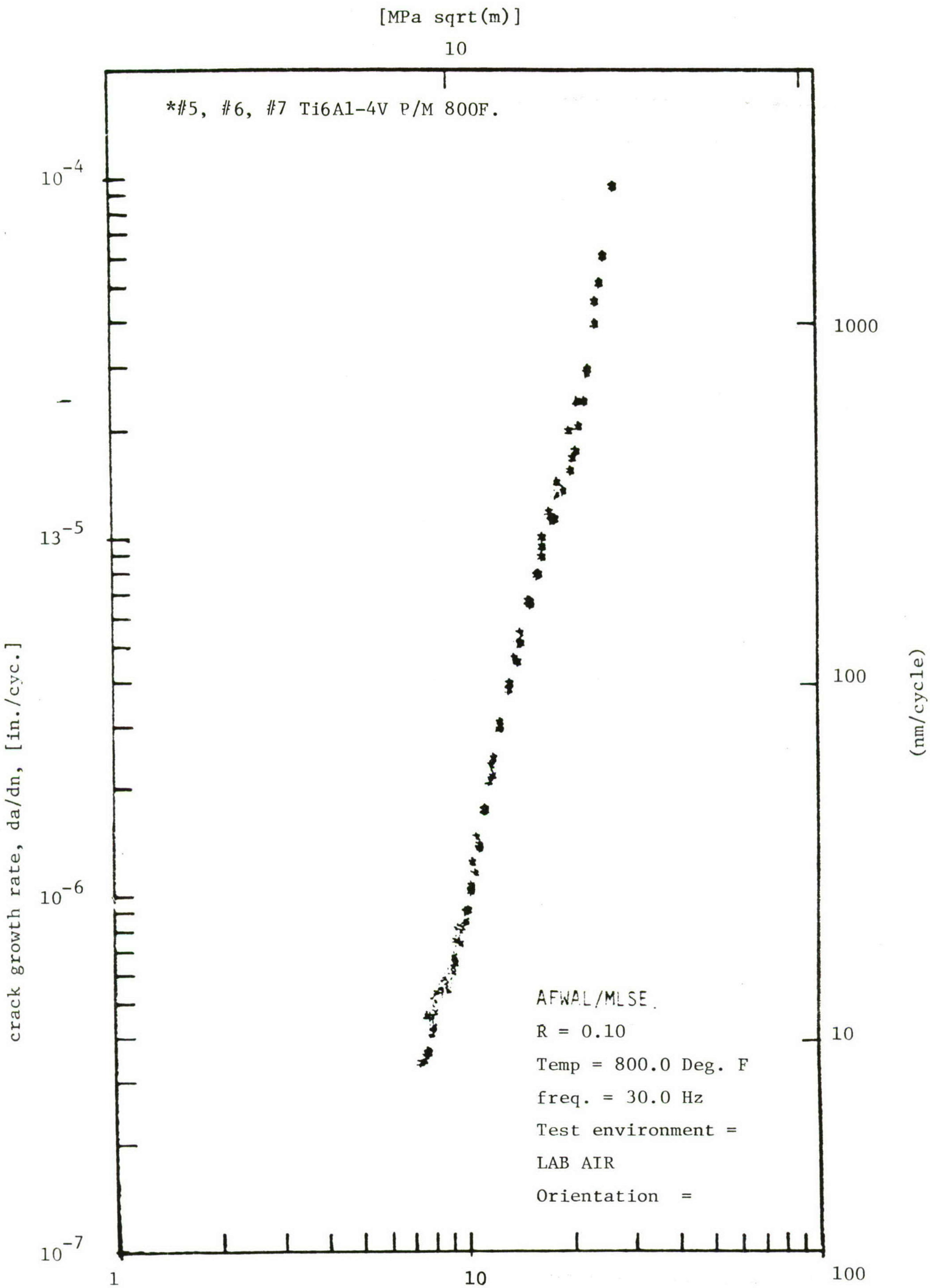


Figure 15. Stress Intensity Range, Delta K, [KSI sqrt (in.)]
AFWAL da/dN @ 800°

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